Nanoscale Based ThermalMagnetic Energy Harvesting

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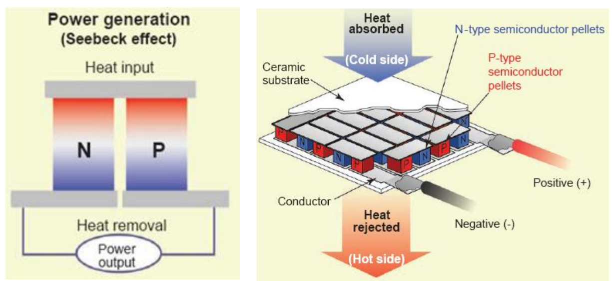
Background

Project goal:

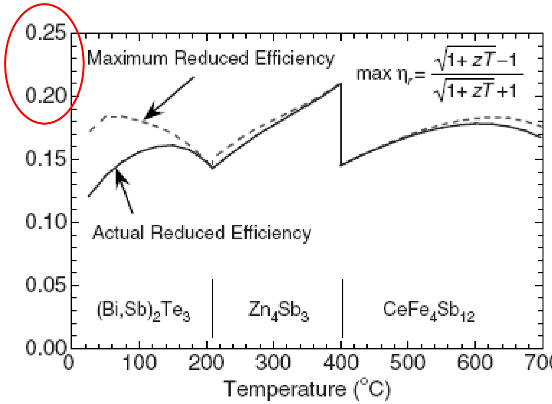
Thermomagnetic Efficiency of 30~50% of Carnot

Thermoelectrics



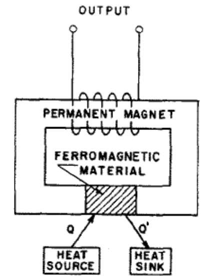
Bell, 2008

Seebeck device: Efficiency is limited at ~20%



Rowe, 2006

Thermomagnetics



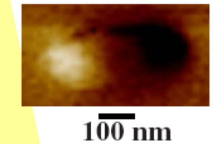
- **1949 Brillouin**
  55% of Carnot
- **1959 Elliot**
  Materials affect performance
- **1984 Kirol**
  Regeneration 75 % of Carnot
- **1988 Solomon**
  Magnetic field increases efficiency
- **2007 UCLA**
  Multi-ferroic and small scale
- **2011 James**
  Multi-ferroic alloy
- **2012 UCLA**
  Single domain

AML's previous works

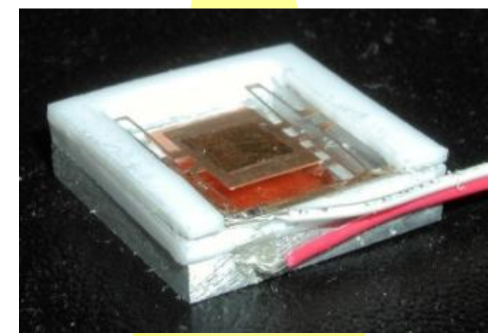
- *Exploit nano-scale phenomena*

Multi-domain

Single domain



- *Thermal-magnetic philosophy*

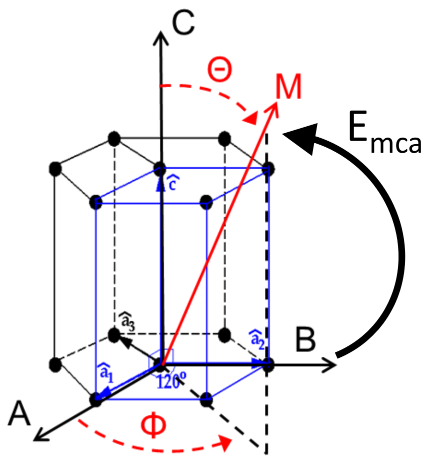


Miniaturized thermomagnetic generator

Application

- *Thermal energy harvesting*

Summary UCLA ThermoMagnetic



Curie Point Gd Harvesting:

Multi-Domain

- $\eta_{rel} \approx 12\%$
- Energy Density = 50 kJ/m^3

Single Domain

- $\eta_{rel} \approx 30\%$
- Energy Density = 105 kJ/m^3

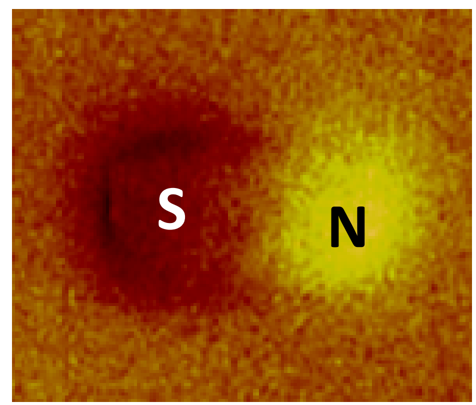
Spin Reorientation:

Gd Single Domain

- trivial

$NdCo_5$ Single Domain

- $\eta_{rel} \approx$ 44%
- Energy Density = 2 MJ/m^3



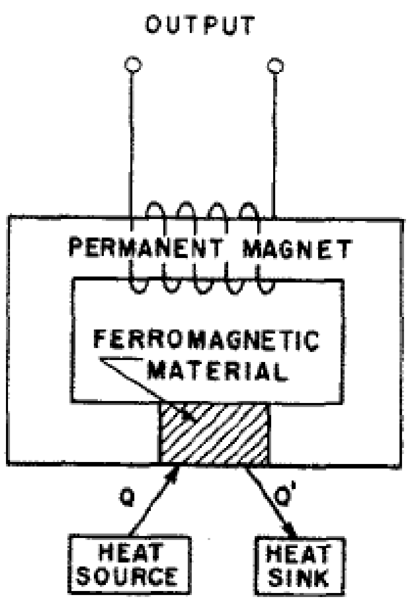
Energy > NdFeB or larger than conventional EM designs

Three Journal articles Three being Written

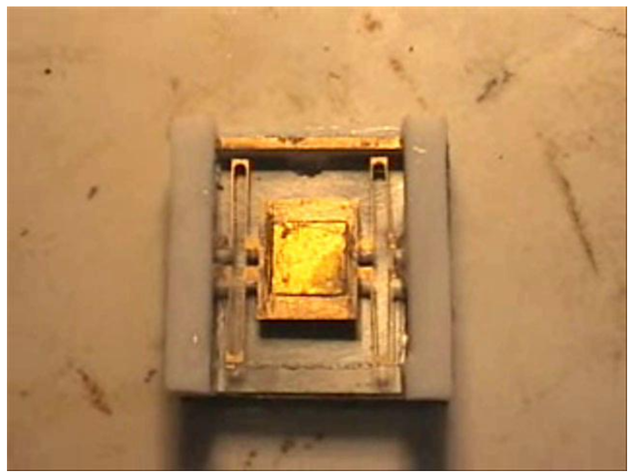
Two Device concepts

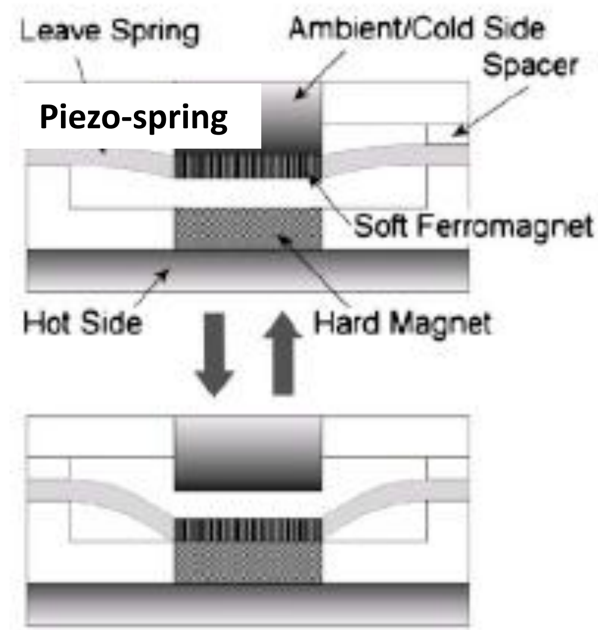
1) Coil (Hoover Dam Approach)
   a) Thermal
   b) Magnetic
   c) Electrical

2) Multi-ferroics (Smart Materials)
   a) Thermal
   b) Magnetic
   c) Mechanic
   d) Electrical



Kirol and Mills, 1984

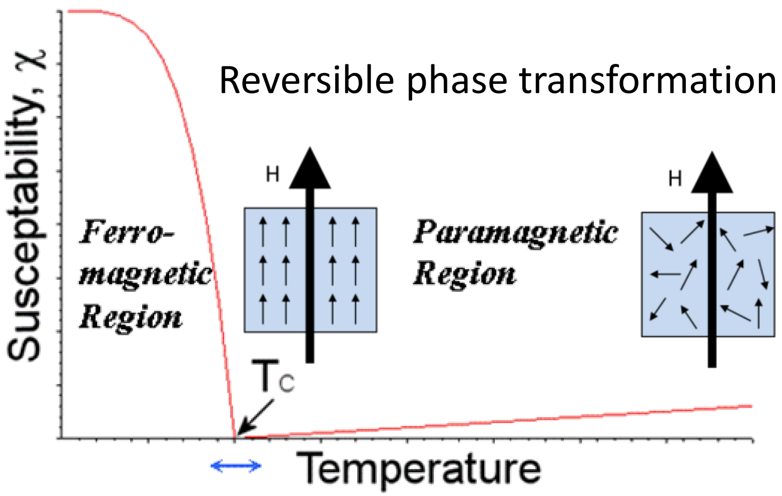


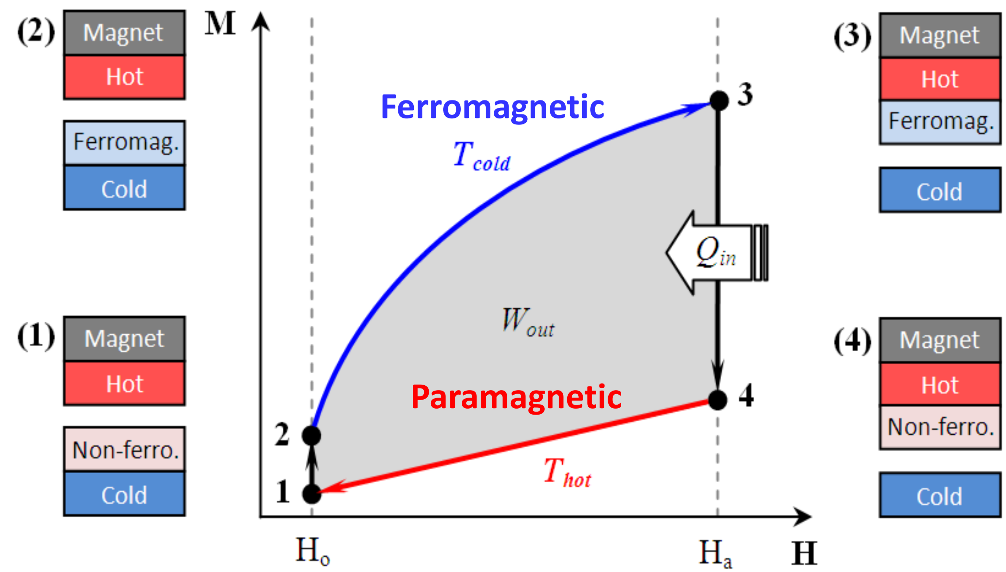


Ujihara et al, 2007

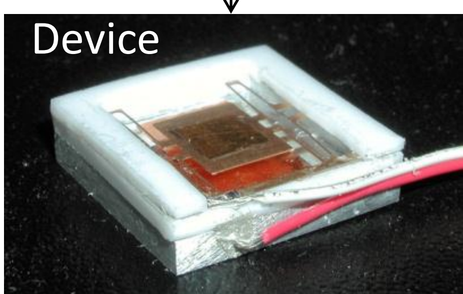
Focus on **efficiency** and **energy** production from thermal to magnetic

Thermomagnetic cycle





$$Q_{in} = \rho \cdot C_p \cdot (T_{hot} - T_{cold})$$



$$\boxed{W_{out} = \oint_{cycle} H dM(T,H)}$$

Q_{out}

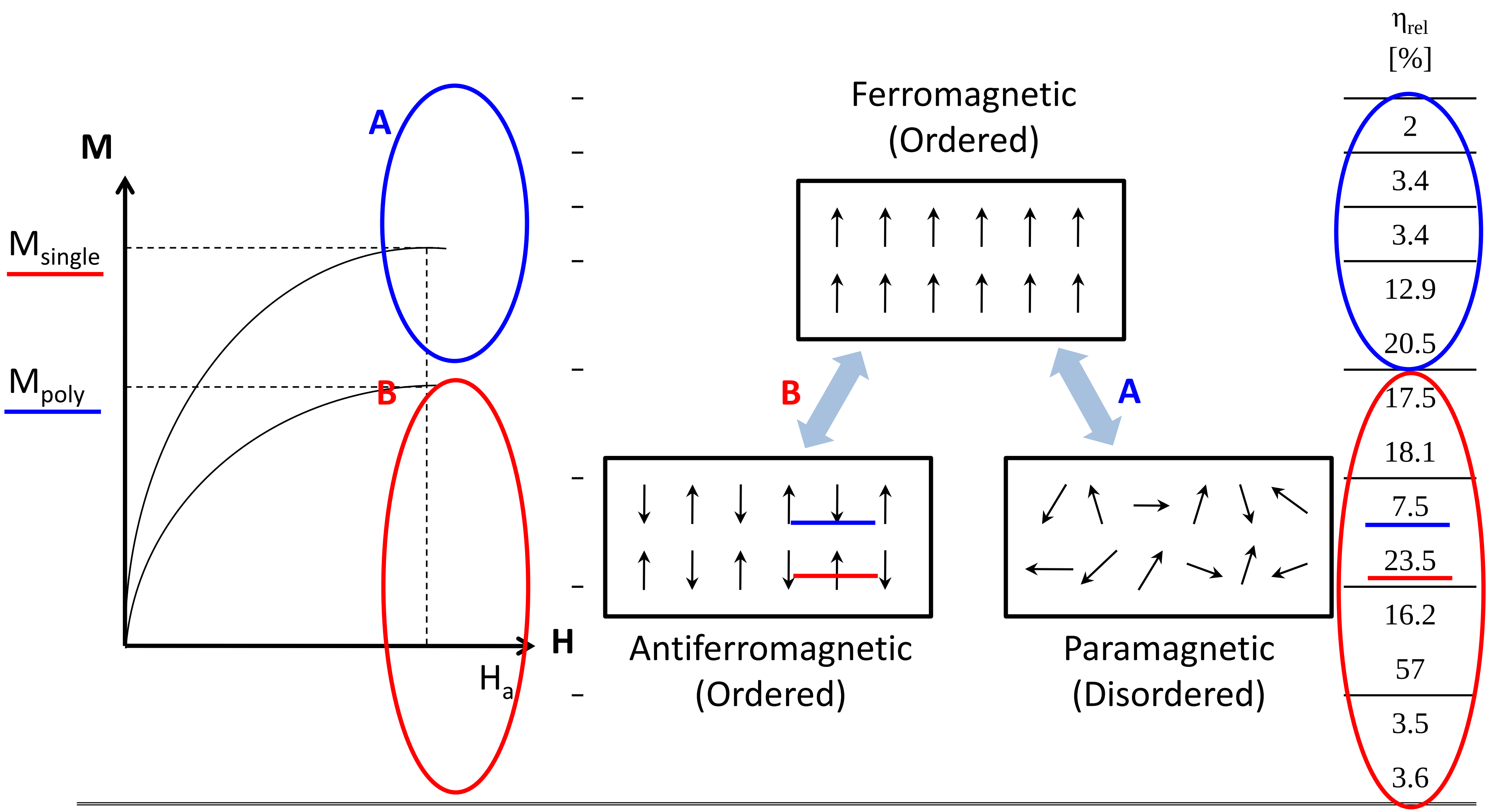
$$\eta_{abs} = \frac{W_{out}}{Q_{in}} = \frac{\textit{Bounded M-H area}}{\rho C_p \Delta T}$$

$$\eta_{rel} = \frac{\eta_{abs}}{\eta_{Carnot}} = \frac{\dfrac{\textit{Bounded M-H area}}{\rho C_p \Delta T}}{\dfrac{\Delta T}{T_{hot}}}$$

(% of Carnot)

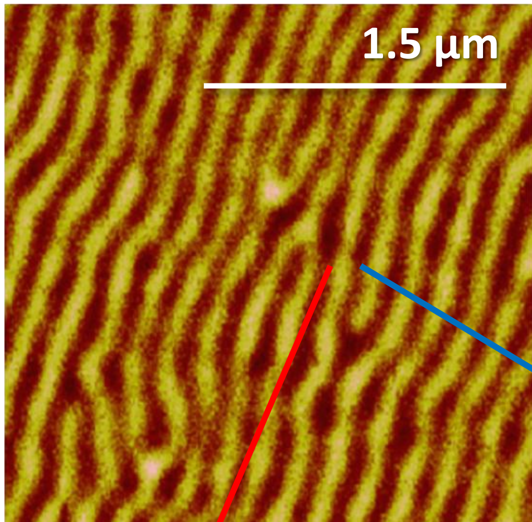
Magneto-thermal Properties of Ferromagnetic Elements

For a thermomagnetic cycle of H = 3000Oe and ΔT = 5K



Single domain – better ordered magnetic state

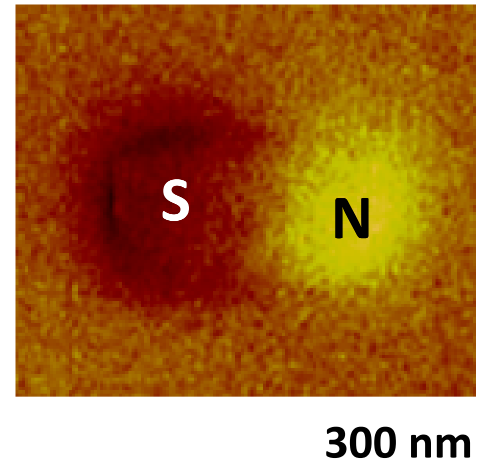
Ni thin film



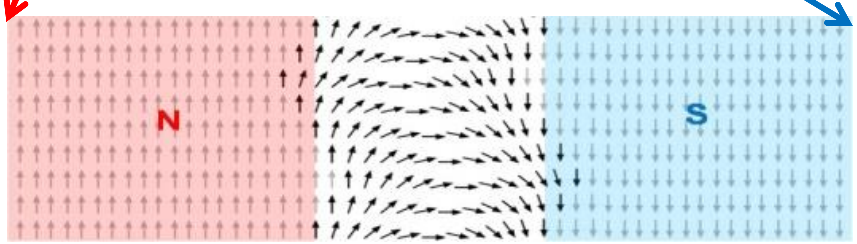
Size ↓

Shape anisotropy ↑

Ni nanobar

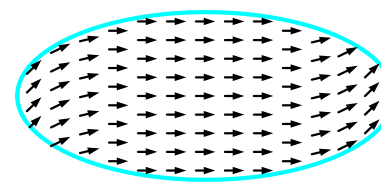


Spin structure



Domain wall

Spin structure

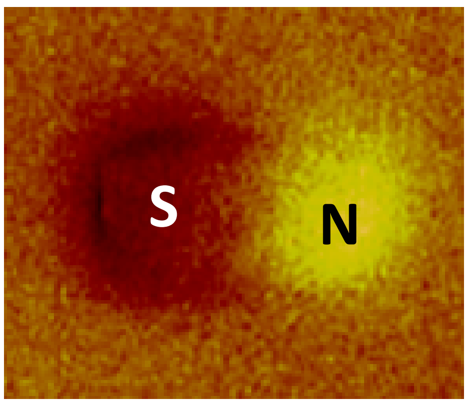


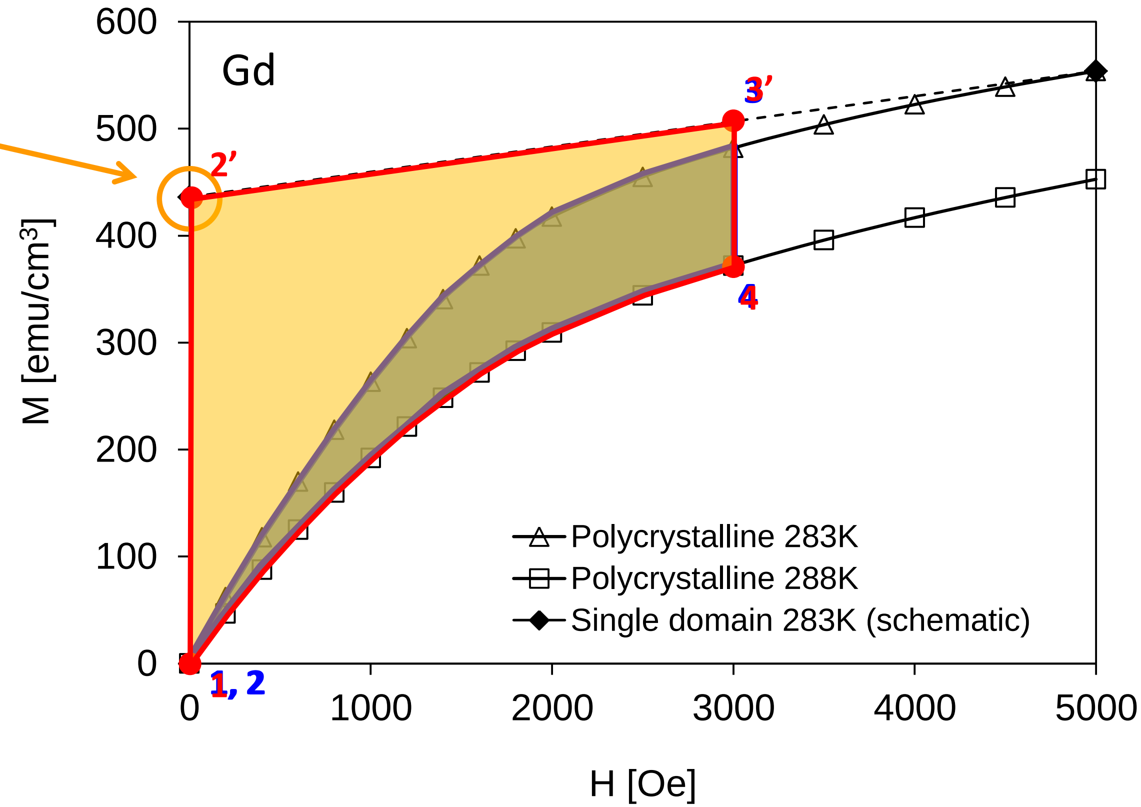
No domain wall

Single domain has high remanence giving higher conversion efficiency!

Single domain improves efficiency

Single domain nanostructure has high remanence



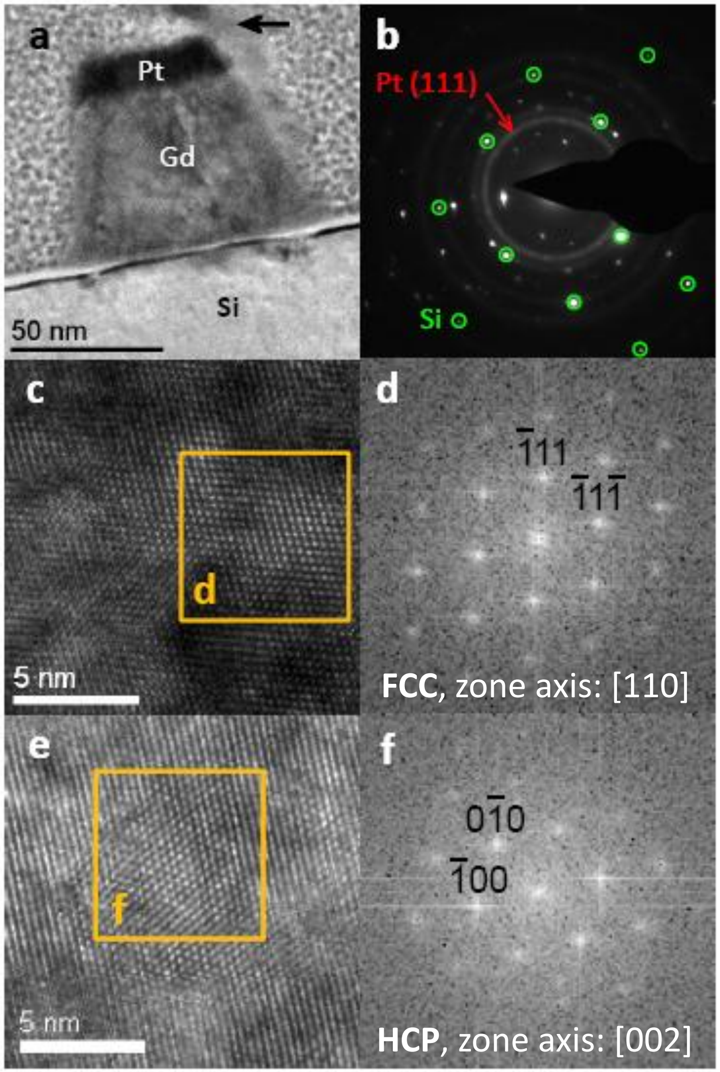


$$\eta_{\mathrm{rel}} = \frac{\eta}{\eta_{Carnot}} = \frac{\dfrac{\text{Bounded M-H area}}{\rho C_p \Delta T}}{\dfrac{\Delta T}{T_{hot}}} \approx \cancel{10\%\ (\text{bulk})}$$

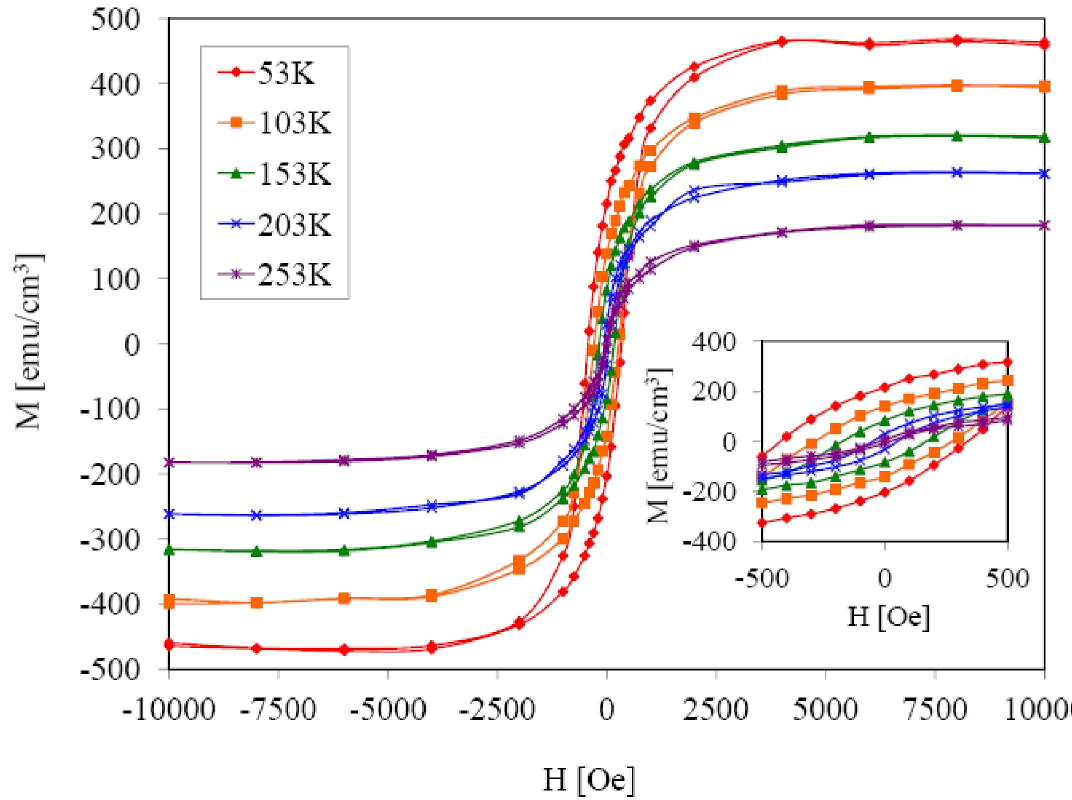
~30% **(Single domain)**

Nanobar structure: Issues

HR-TEM analysis:



M-H curves of Gd nanobar array



ISSUES
- ✓ Significant M_s reduction
- ✓ HCP to FCC transformation at the nanoscale
- ✓ Surface oxidation – How to prevent?

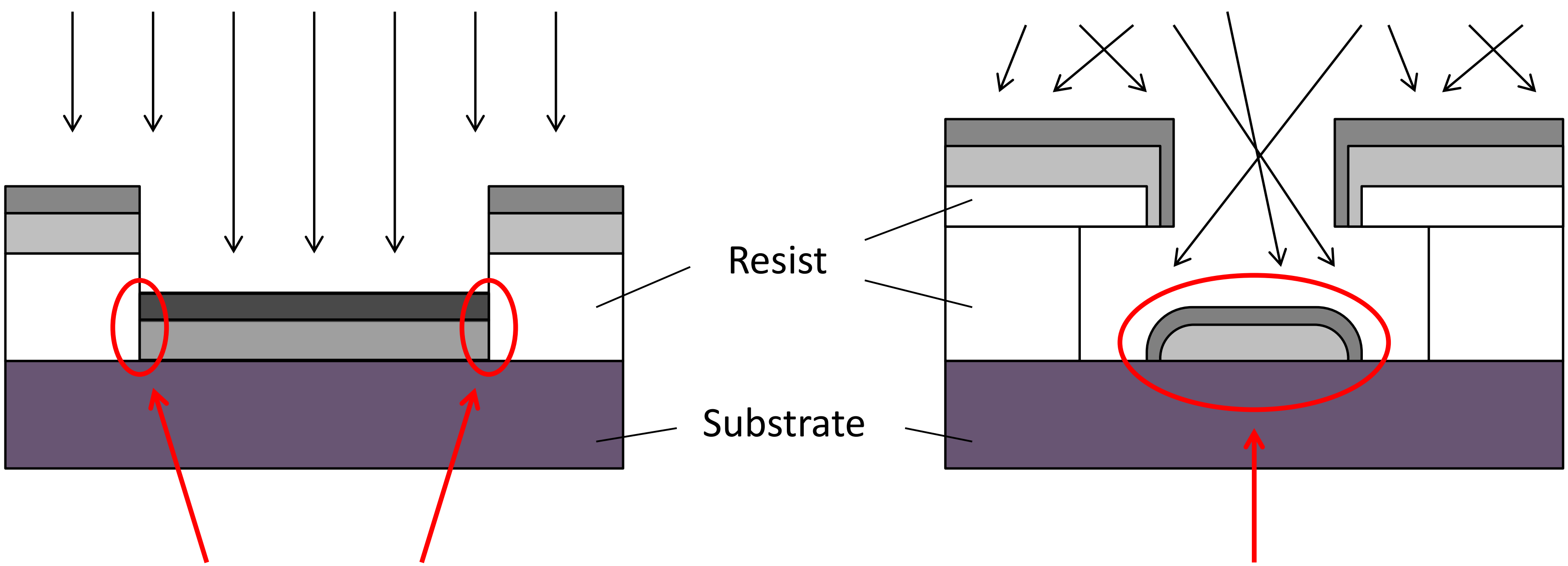
Nanobar structure: New process

Problem

Ebeam evaporation

Solution

Sputtering



Inevitable sidewall exposure

Full coverage

Gd Nanostructures to be tested this month

Basic Science Questions

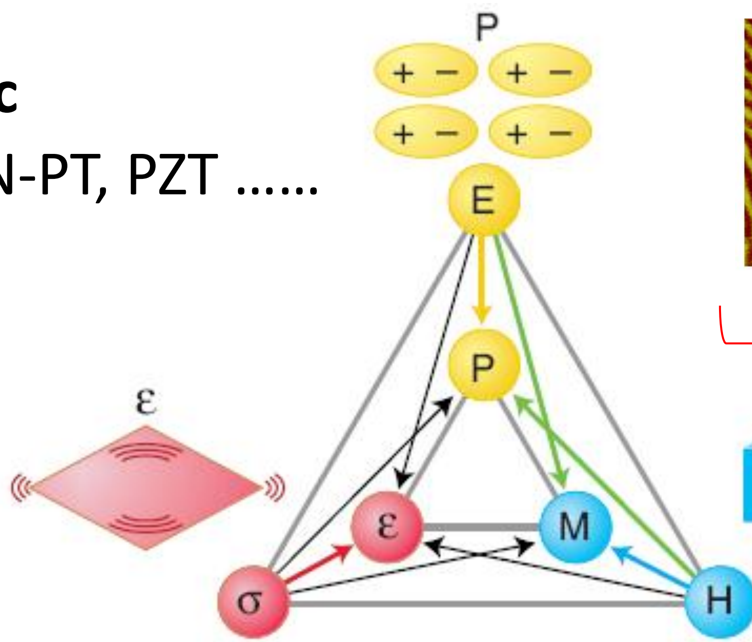
	Ni	Gd
Electron configurations	[Ar] $4s^2$**$3d^8$**	[Xe] **$4f^7$** $5d^1$ $6s^2$
Source of magnetic moment	3d shell	4f shell
Relative shell position	Outmost shell	Inner shell
Exchange coupling	Direct exchange	*Indirect* exchange
Exchange length	~10 nm	?
Single domain	Exist	?
Superparamagnetic size	~20 nm	?

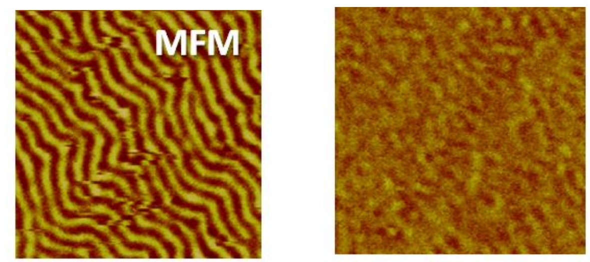
Multiferroic Energy Transfer

Can we Induce Single Domain from Multi-Domain Magnetic Structures

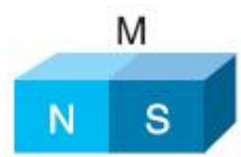
Ferroelectric

PMN-PT,PZN-PT, PZT ……





0 kV/cm 8 kV/cm



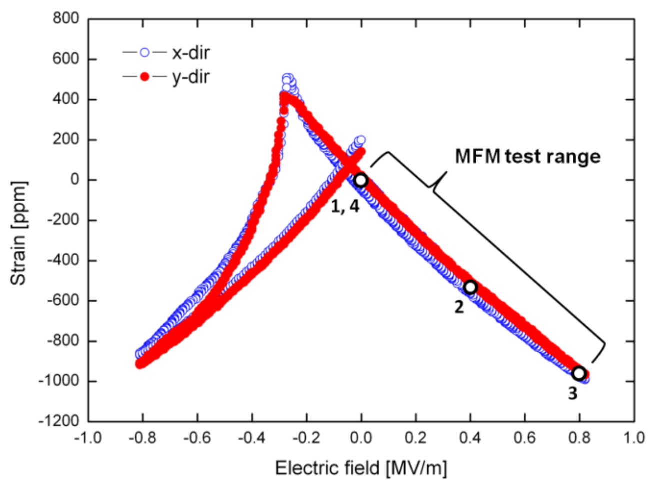
E-field control single domain?

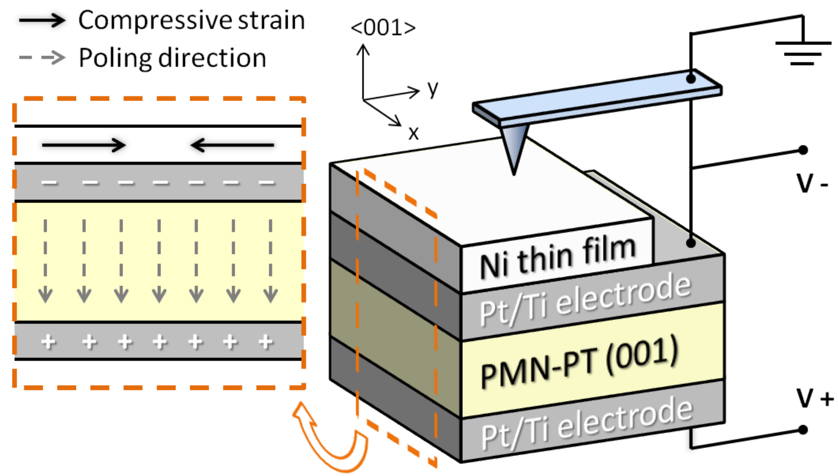
Spaldin and Fiebig, Science, 2005

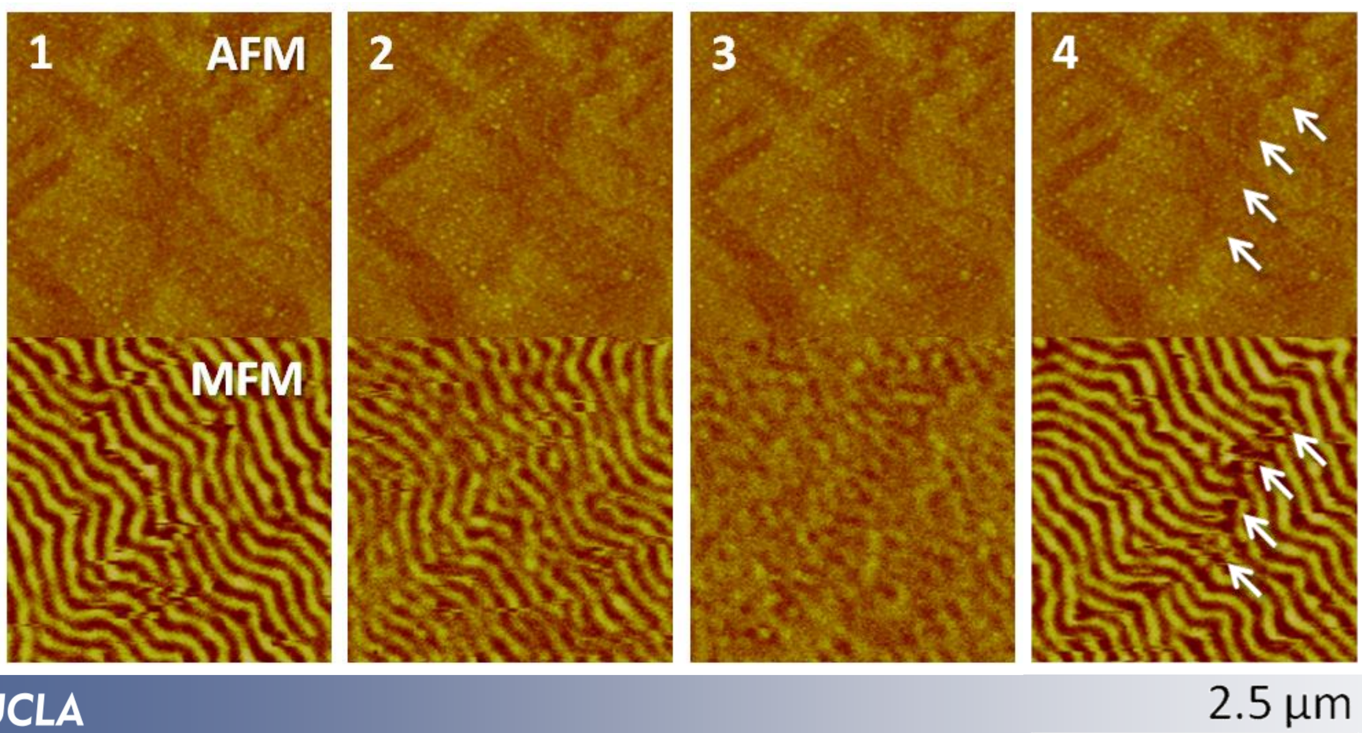
Ferromagnetic

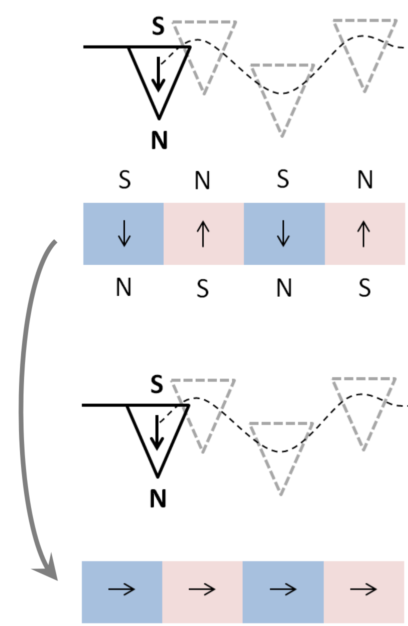
Ni, Gd, Terfenol-D

Experimental Demonstration



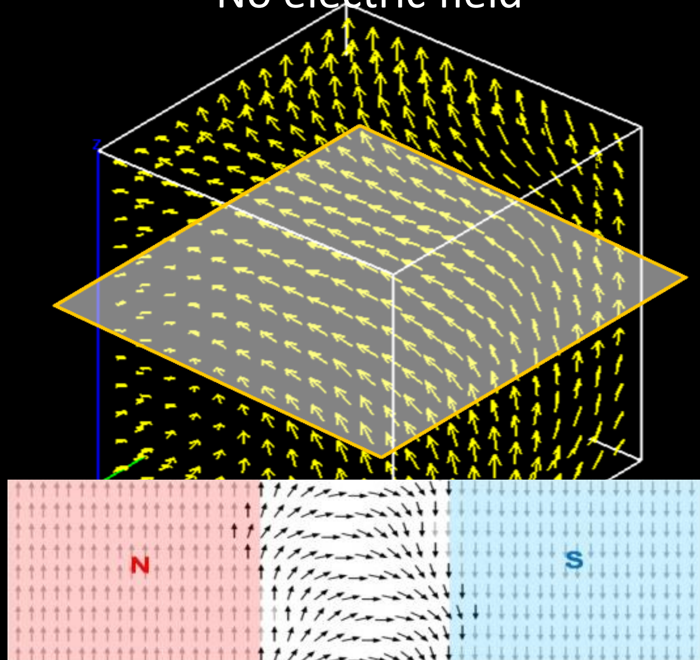




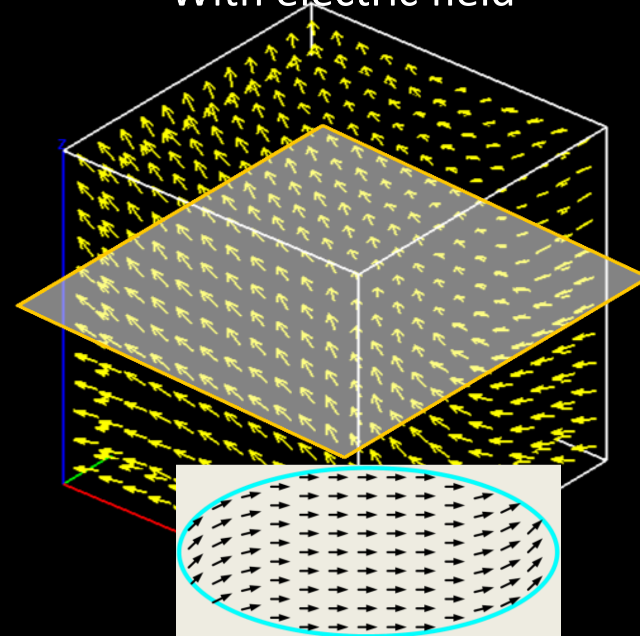


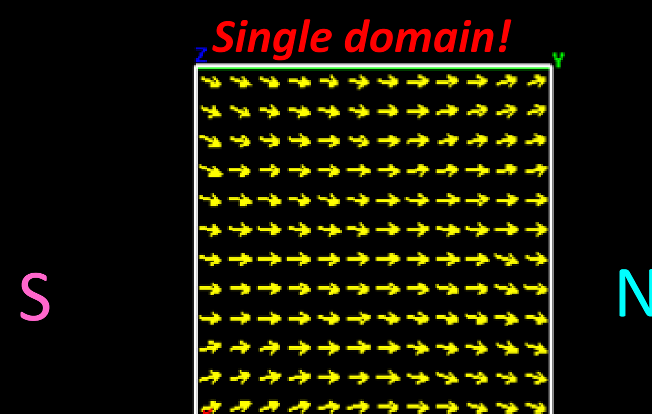
Analytical Model Development

No electric field



With electric field





Modeling

1. LLG micromagnetics
2. Mechanical Equilibrium
3. Control magnetic instability

Higher efficiency possible?

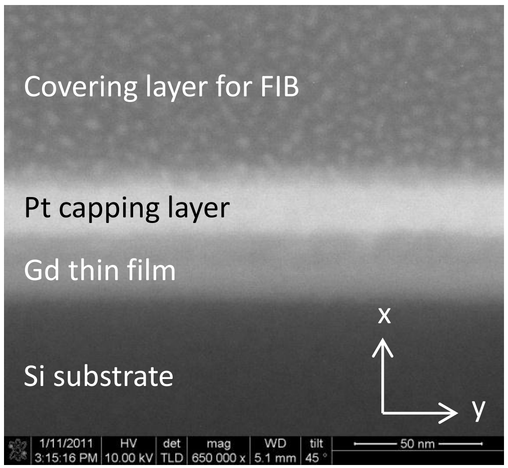
<u>Spin-reorientation</u>

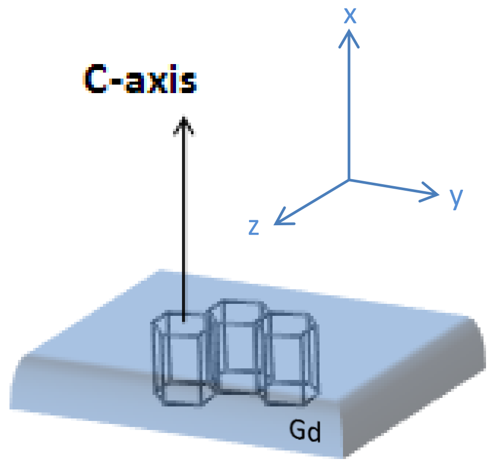
- Gd

- $NdCo_5$

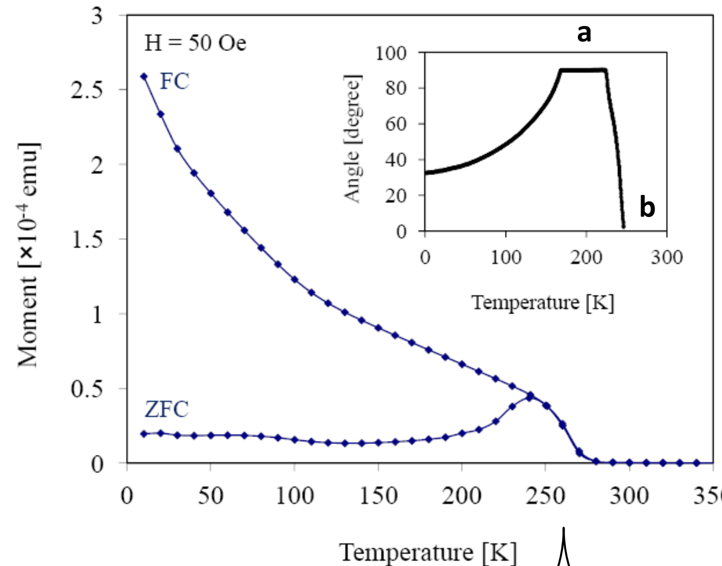
Spin-reorientation: Gd thin film

FIB/SEM image

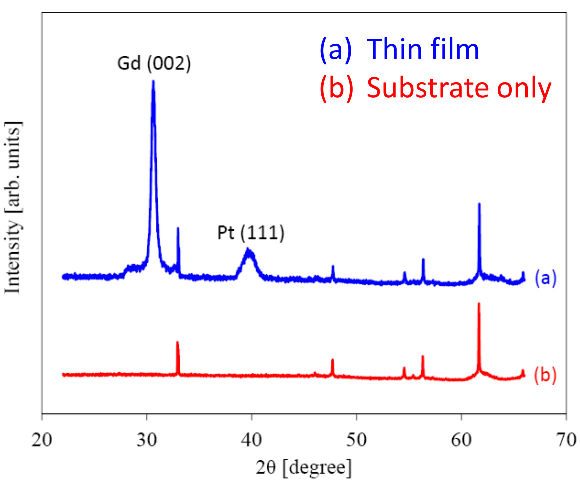


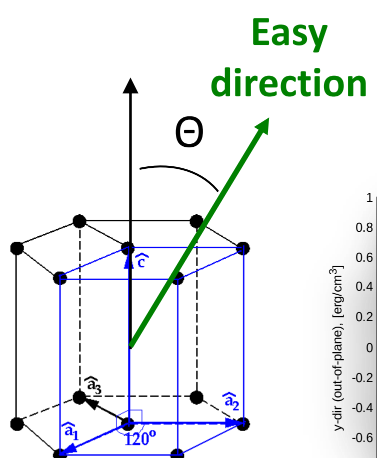


Magnetocrystalline , function of temp.

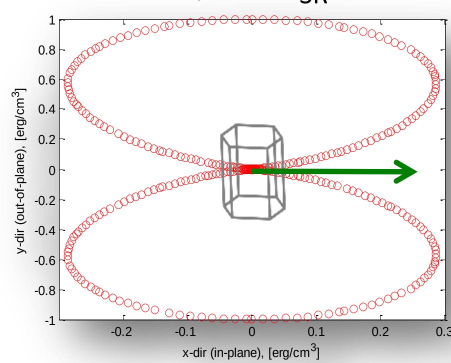


XRD: Textured crystal structure

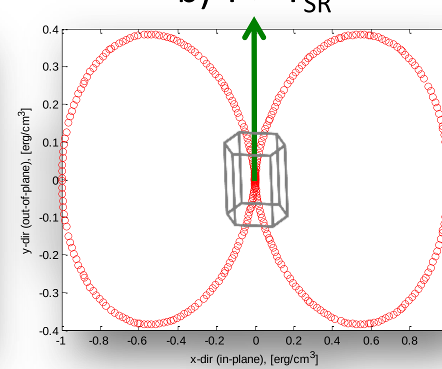




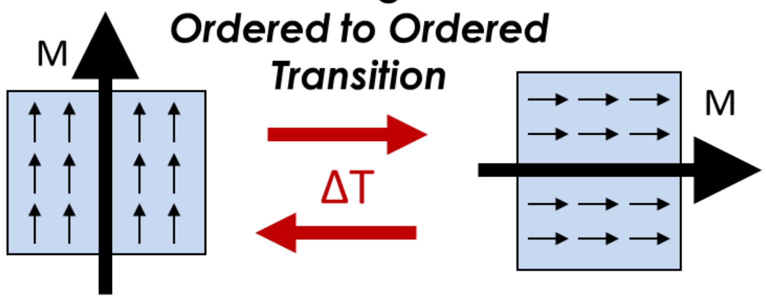
a) $T < T_{SR}$

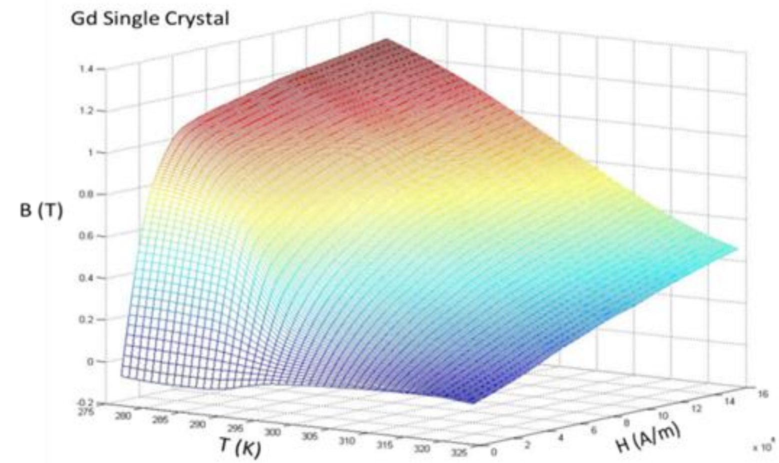


b) $T > T_{SR}$

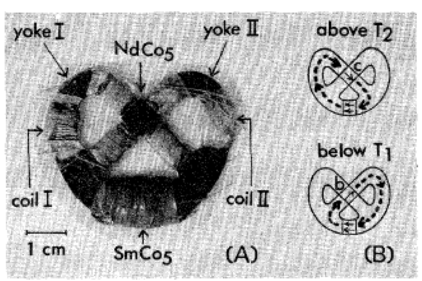


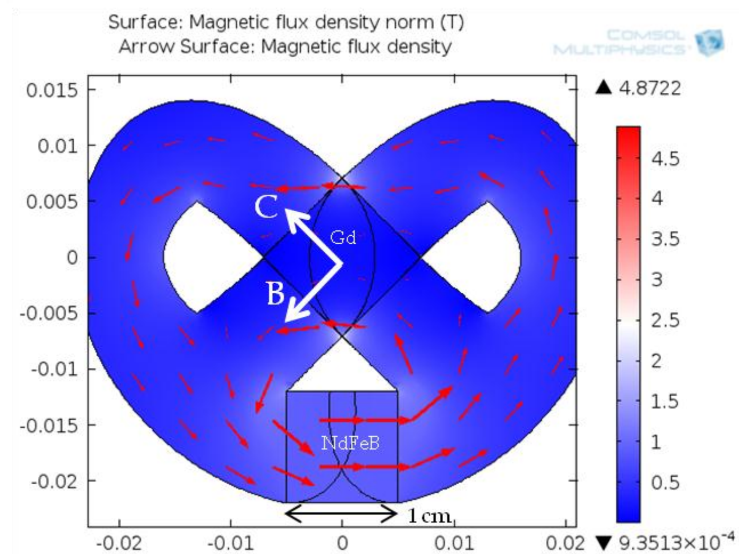
Moving to spin-reorientation harvesting



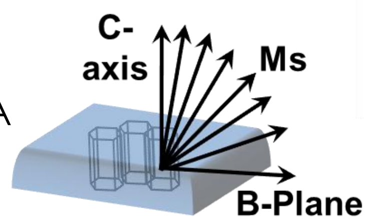


- **1968 Spin Reorientation:** Horner and Varma
- **1968 1st SR Application:** Ohkoshi: 8.6% of Carnot





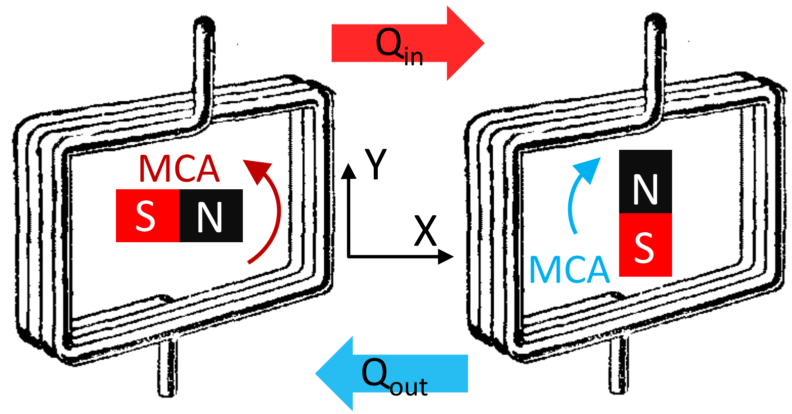
- **2010 NdCo5 Thin Flims:** M. Seifert
- **2012 Textured Gd Thin Flims:** UCLA



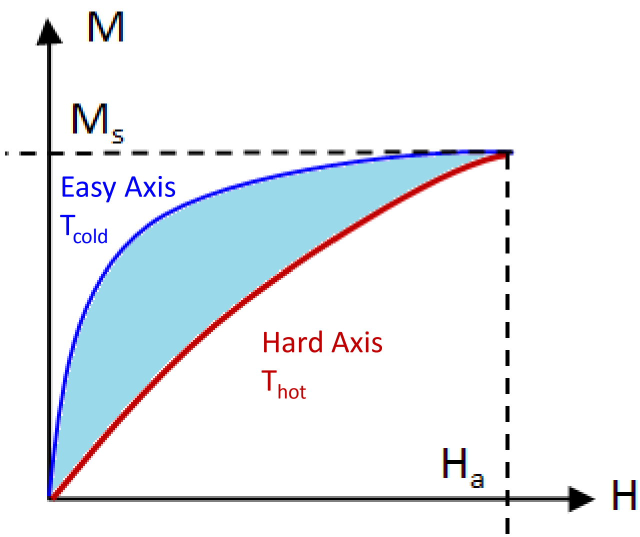
Change of MCA energy in Gd

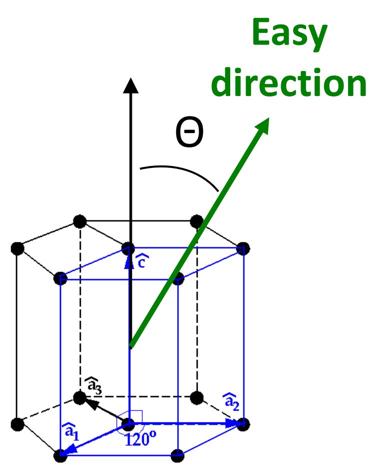
- The easy axis of magnetization is dependent on the minimum MCA energy state

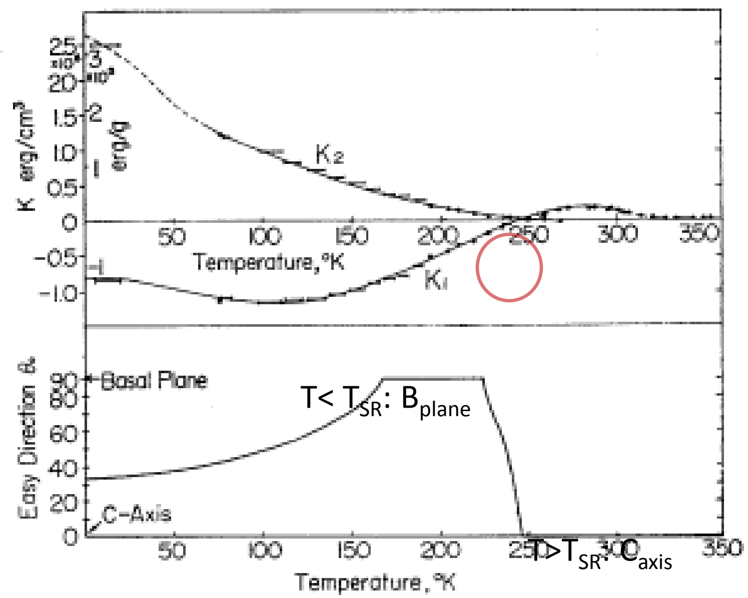
- MCA energy can be thought of as "doing work" on the magnetic direction



Solving $\frac{dE_{mag}}{d\theta} = 0 \Rightarrow \theta = \pm \arccos\left(\sqrt{\frac{K_1(T) + 2K_2(T)}{2K_2(T)}}\right)$







Problem very little energy available Gd 5kJ/m(3)

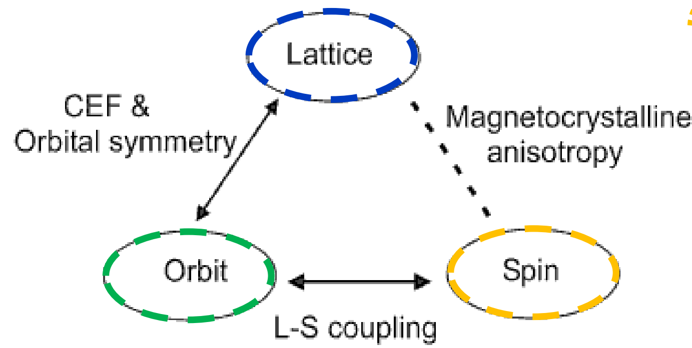
Gd vs. $NdCo_5$

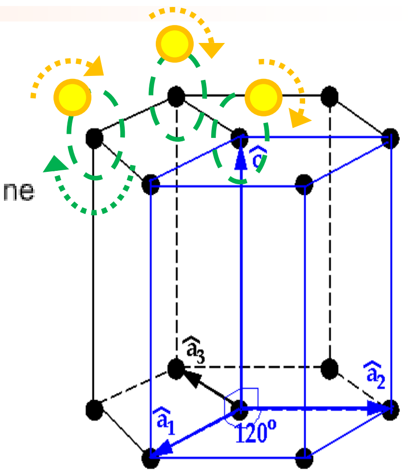
Rare earth magnets

- Magnetization controlled by anisotropic 4f shell

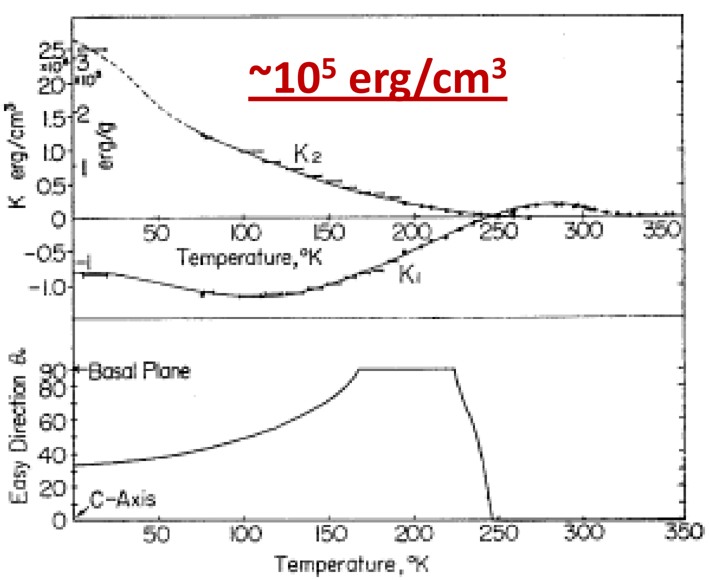
Gadolinium

- Has a half-filled 4f shell -> Very low orbit moment resulting low MCA energy than other RE magnets



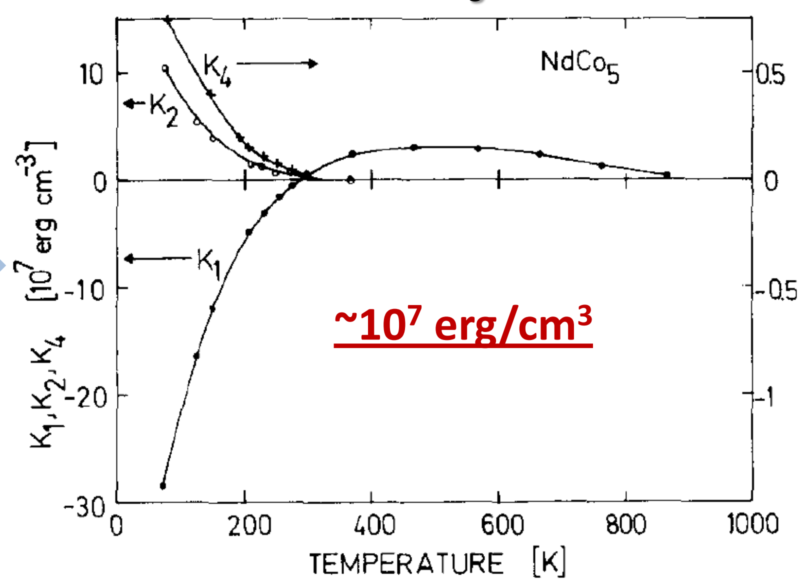


Gadolinium



C.D. Graham, Magnetocrystalline Anisotropy of Gadolinium

$NdCo_5$

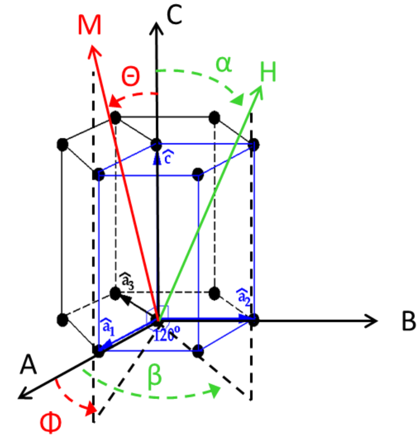


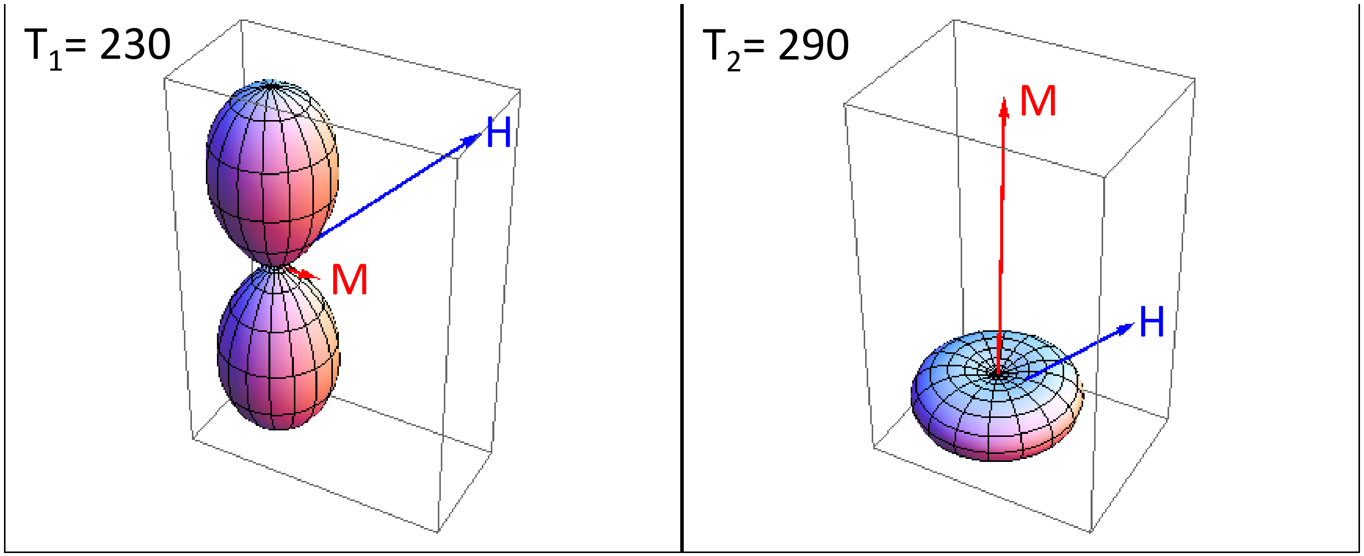
H.P Klein, Magnetocrystalline Anisotropy of Light RE Cobalt Compounds

Analytical Model Single Domain $NdCo_5$

Magnetic Energy Model

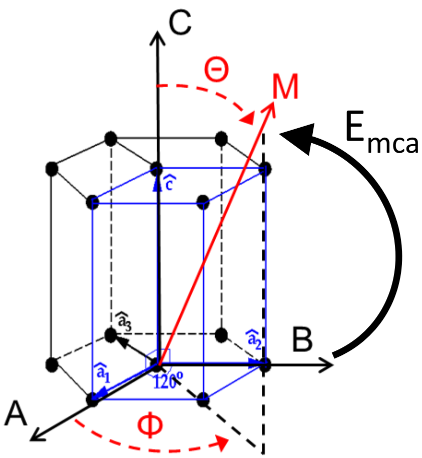
- $E_{mag}(\theta,\phi,\alpha,\beta,T,H,N) = E_{ms}(\theta,\phi,\alpha,\beta,H) + E_{mca}(\theta,\phi,T) + Es_h(\theta,\phi,\mathrm{N})$
- Solving $\frac{dE_{mag}}{d\theta} = 0$ gives $\theta_{easy}(T)$ or the direction of M(T)





- Energy output potential $\mathbf{E_{out}} \approx$ **2 MJ/m³** yielding $\boldsymbol{\eta_{rel}} \approx$ **44%**
- **Currently fabricating film to test**

Summary UCLA ThermoMagnetic



Curie Point Harvesting:

Multi-Domain

- $\eta_{rel} \approx 12\%$
- Energy Density = 50 kJ/m^3

Single Domain

- $\eta_{rel} \approx 30\%$
- Energy Density = 105 kJ/m^3

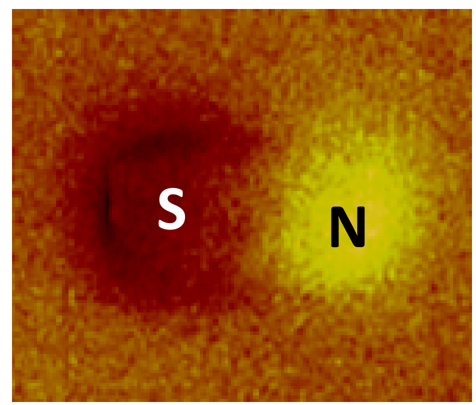
Spin Reorientation:

Gd Single Domain

- $\eta_{rel} < 1\%$
- Energy Density = 12 kJ/m^3

$NdCo_5$ Single Domain

- $\eta_{rel} \approx$ 44%
- Energy Density = 2 MJ/m^3



Energy Larger Than NdFeB or large than conventional EM designs

Summary

- **ThermalMagnetics represents a very promising energy harvesting methodology**
- **Efficiency increases by 3X using single domain**
  - More energy output nanobar structure
  - Multiferroic structure
- **Spin-reorientation**
  - MCA dominates work output
  - $NdCo_5$ superior than Gd in terms of MCA change
  - Very large energy density present in $NdCo_5$

The Nation that Controls Magnetism will Control the Universe.